

## PIEZOELECTRICALLY ACTUATED MICROVALVES FOR MICROPROPULSION APPLICATIONS

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### ABSTRACT

This paper presents a piezoelectric microvalve technology with a high pressure handling capability for micropropulsion applications. The device is a normally closed valve fabricated mostly by the micromachining of silicon. The valve consists of a custom designed piezoelectric stack actuator bonded onto silicon valve components in a stainless steel housing. Major elements of the silicon valve design include narrow edge seating rings and tensile-stressed silicon tethers that contribute to the desired normally closed leak-tight operation. No leak has been detected from a soap solution test at differential pressures of 0~500 psi for a normally closed valve structure, indicating a leak rate of 0.001sccm or lower has been achieved. Piezoelectric operation has been successfully demonstrated at a differential pressure of 500 psi. A flow rate of 20 sccm at 100 psi has been obtained at 50 V.

### INTRODUCTION

Miniaturized, micro/nano spacecraft concepts are of great interest in the aerospace community. Any reduction in the mass and size of a space instrument or subsystem results in nearly exponential savings in launch costs as well as significant increases in mission duration. In order to enable the construction of such 'microspacecraft', each subsystem will have to be reduced in size and adapted in function to fit within the spacecraft size and mass envelope, and thereby require extensive miniaturization. Furthermore, thrust levels and impulse bits will have to be reduced in magnitude. The reduction in thrust levels and impulse bits requires fine control of very small propellant flow rates. Microvalves are needed to

control these propellant flows. Table 1 shows the nominal valve requirements for micropropulsion applications (Mueller, *et al.*, 1997). Given the severely limited power constraints of the overall micropropulsion system, microvalves with "normally closed" operation are needed in order to consume power only during opening or closing process. Solenoid valves have been refined by decades of technology development, but they suffer from fundamental limitations such as volume and power consumption. Many turns of copper wire with a volume of a high-permeability core material are required to generate a high actuation force, making the actuator larger and heavier than desired for many applications.

Typical MEMS-based microvalves are generally well within the requisite power consumption and mass requirements. However, they function marginally with regard to valve actuation time (Zdeblick, M.J., *et al.*, 1994; Barth, P.W., 1995; Barth, P.W., 1995; Yang, X., *et al.*, 1997; Jerman, H., 1990; Franz, J., *et al.*, 1995; Ray, C., *et al.*, 1992; Busch, *et al.*, 1990; Johnson, D., *et al.*, 1998), seating force (Huff, M., *et al.*, 1993; Huff, M., *et al.*, 1992; Shikida, M., *et al.*, 1993; Ohnstein, T., *et al.*, 1990; Kluge, S., *et al.*, 1998), or pressure handling capability<sup>2-25</sup>. Slow valve actuation time would lead to long thruster on-times and wide impulse bits. These valves also suffer from the risk of un-commanded valve opening if ambient heating or cooling occurs, resulting in uncontrolled initiation of the actuation mechanism. Microvalves without adequate seating are exposed to severe problems in leakage and pressure handling capability. Most MEMS-based microvalves reported previously have shown marginal valve seating at high pressures, pointing to the need for improved valve designs. Significant efforts are required for the development of the microvalves meeting these challenging requirements. In this paper, we

demonstrate a leak-tight piezoelectric microvalve for high differential pressure operations.

Table 1 Valve requirements for NASA's Deep Space Miniature Spacecraft Propulsion

PARAMETER	VALUE
Leak Rate	< 0.3 scc/hr Helium
Actuation Speed	< 10 milliseconds
Inlet Pressure (liquid)	0 – 300 psi
Test effluents	Gas
Power Consumption	< 1 W
Weight	< 10 gm
Temperature	-120 °C to 200 °C
Particulates	< 5.0 micron

## DESIGN OF MICROVALVE

The piezoelectric microvalve described in this paper consists of a seat plate, a boss plate and an actuator as given in Figure 1. The microvalve components do not contain fragile membranes in order to allow high-pressure operation. Major elements of the microvalve design include seating configuration and narrow seat rings. The seating configuration is provided by an initial opening pressure attributable to the tensile stress in the silicon tether extended by the valve seat as shown in Figure 2. The narrow rings reduce contact area, increasing the seating pressure and consequently reducing internal leaks. An additional advantage of the narrow/hard-seat design is that contact pressures may be high enough to crush contaminant particles, thereby also reducing the leakage attributable to contaminants in the flow. The boss plate has a 2  $\mu\text{m}$  thick Plasma Enhanced Chemical Vapor Deposition (PECVD) oxide layer as a hard seat material in the boss-center plate. The outer part of the boss plate is a metal-to-metal bond to the seat plate. The boss-center plate, which is slightly thicker than outer part is pushed down toward the seat plate, enhancing a leak-tight valve operation. The piezoelectric stack actuator exhibits a very high block-pressure (50 MPa in this case), providing enough force to overcome the high differential pressure in addition to the downward bending stress from the boss plate. As shown in Figure 3, the custom designed stack of piezoelectric actuators consists of active zones and inactive central part. A piezoelectric stack with mechanically separated (by deep U-grooves) active zones is bonded to the boss plate within a rigid housing. Application of 50V to the stack causes the active zones to vertically expand by 5 $\mu\text{m}$ , lifting the boss center plate (bonded to the inactive zone in the center part of the stack) away from the seat plate. This action creates a channel between the two openings, allowing the passage of fluids. Since the piezoelectric element is essentially a stacked capacitor, the

actuator does not consume power when not moving, thus making it possible to achieve a zero-power, normally-closed valve system.

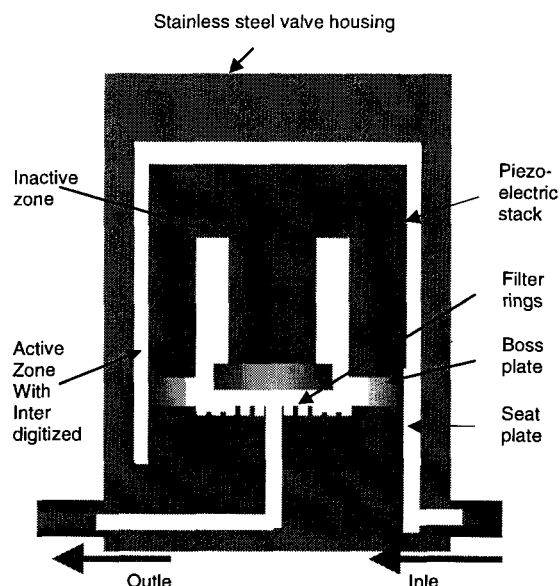


Figure 1 Schematic cross-section of the piezoelectric MEMS valve. The valve is designed to provide the leak-tight operation at high pressures, provided by a robust actuator construction located within a rigid valve housing.

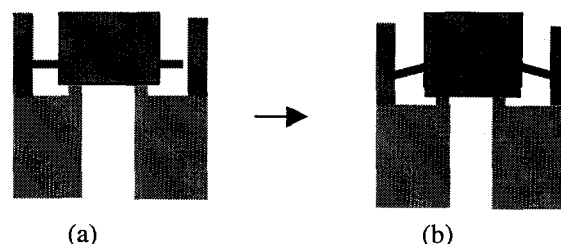


Figure 2 Hard seating configurations. (a) Without an additional layer (b) With an additional layer: A leak-tight operation can be achieved by providing a slightly thicker boss-center. The microvalve has an initial opening pressure attributable to the tensile stress in the thick silicon tether extended by the valve seat (by incorporation of the slightly thicker boss-center).

## IMPLEMENTATION

The microvalve fabrication process sequence is briefly described as follows. A Deep Reactive Ion Etch (DRIE) is used to define the seating rings on the valve seat. The seat wafer is then etched from the backside to open up vias for the ports. These are metallized and patterned to define the bonding surfaces. The boss (or valve flap) wafer is then patterned from the topside to define the boss, which is released in a final DRIE

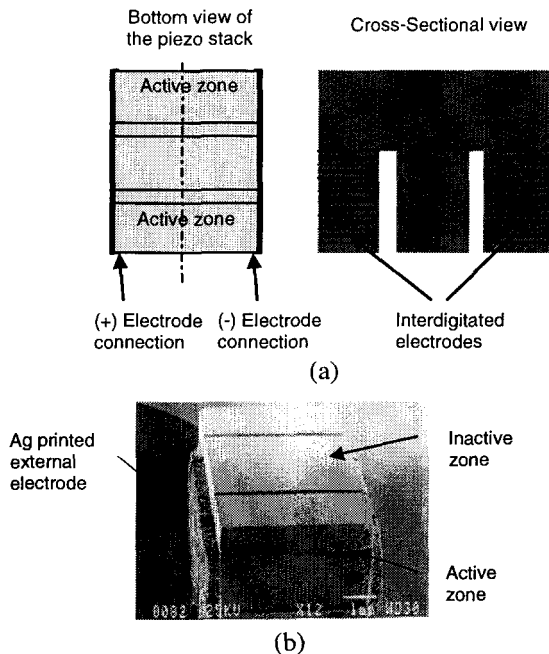


Figure 3 Structural details of a laminated piezoelectric stack. (a) The bottom and cross-sectional views of a piezoelectric stack with mechanically separated active zones. The active zones contain interdigitated Pt electrodes connected through screen-printed external Ag electrodes. (b) A SEM image of a piezoelectric stack actuator.

etch. PECVD oxide is deposited and patterned on the boss-center plate, followed by the deposition and patterning of bonding metals on the outer part of the boss and seat plates. The boss and seat wafers are then bonded to create a sealed and yet variable passage between the inlet and the outlet. This microfabricated structure, together with the piezoelectric actuator, is the primary valve component. Figure 4 shows the microfabricated silicon valve components.

The microfabricated valve components are bonded to stainless steel fixtures, which are hermetically sealed using an epoxy (Hysol E/A 9394, cured at room temperature) for flow tests at high pressures. Figure 5 shows the stainless steel valve housing for high-pressure leak test. The flow test set up is shown in Figure 6. Nitrogen gas pressure at the inlet is varied precisely using a series of gauges and regulators (MKS precision flow measuring instruments). The resolution of the precision flow sensor used in this experiment is 0.1 sccm. Thus, a soap solution has been used to verify the leak rate as low as 0.001 sccm. As shown in Figure 7, no leak has been detected from the soup solution test at 0 ~ 500 psi. The valve has been successfully opened during operations from 0 to 500 psi, before and after the leak test at high pressures, without observable degradation in the performance. Figure 8 presents the nitrogen flow rates of a valve actuated by the piezoelectric stack actuator. The measured flow rate at 100 psi is 20 sccm at 50 V.

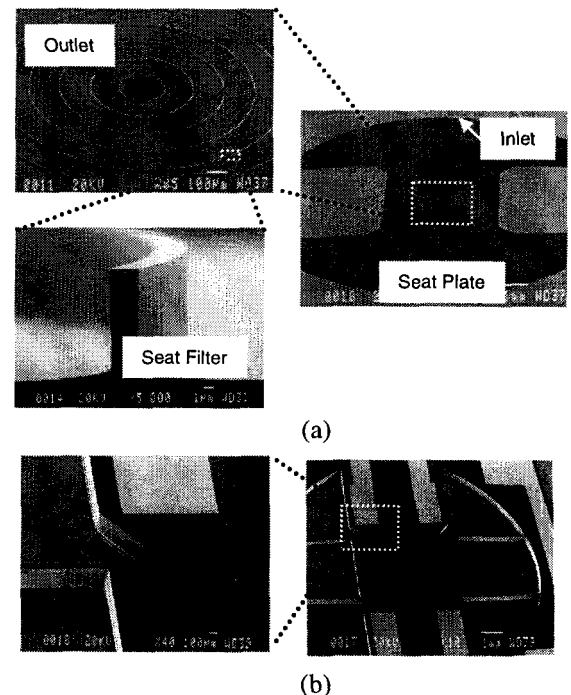


Figure 4 SEM images of (a) seat and (b) boss dies. The top surfaces of the rings are covered by 0.5 micron thick oxide. This design can tolerate scratches over several rings without allowing leaks to develop.

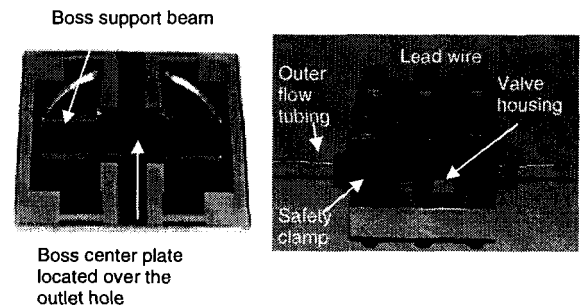


Figure 5 Pictures of a completed silicon valve element and a valve housing. (a) The boss plate is thermal-compression bonded onto the seat plate to constitute the silicon valve element. The piezoelectric stack (not shown in this photo) is placed over the boss plate. (b) The rigid valve housing allows no external leak at 1000 psi. (verified by helium leak testing)

## CONCLUSIONS

A leak-tight, piezoelectrically operated microvalve has been developed for high differential pressure applications such as micropropulsion. An extremely low leak rate ( $< 0.001$  sccm) of a normally closed valve has been demonstrated for pressures in the range of 0~500 psi. The availability of such microvalves is expected to "open several doors" in micropropulsion and other microfluidics applications.

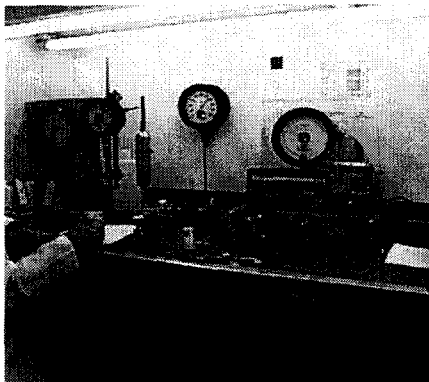


Figure 6 Flow test equipments. Leak tests and flow measurements are performed with nitrogen gas. High-pressure leak testing (~3000 psi) can be performed using this set up.

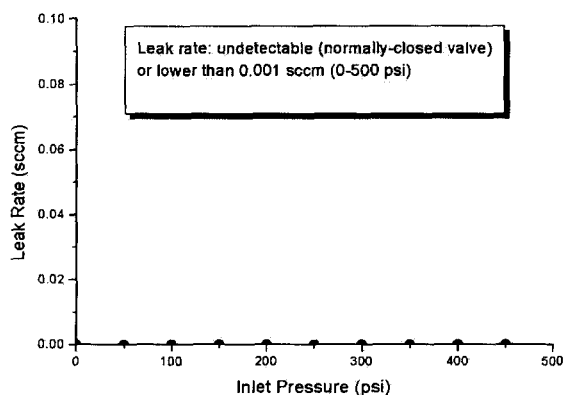


Figure 7 Internal leak rate of a non-actuated valve is undetectable (< 0.001 sccm) at inlet pressures up to 500 psi.

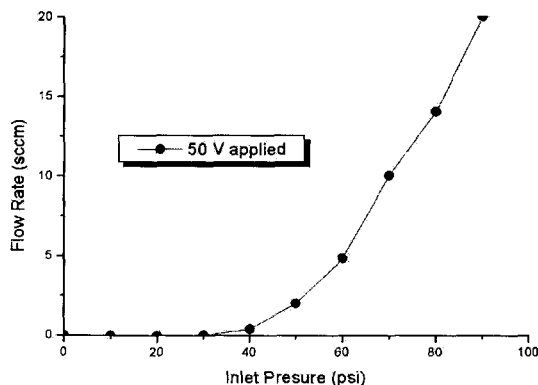


Figure 8 Flow rate of the actuated valve. The piezoelectric microvalve is successfully operated at 500 psi.

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